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Development of Techniques and Equipment to Measure Optical Characteristics of Agricultural Plants & Products

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DEVELOPMENT OF TECHNIQUES AND EQUIPMENT TO MEASURE OPTICAL CHARACTERISTICS OF AGRICULTURAL PLANTS AND PRODUCTS

E. J. BRACH

SUMMARY

Engineering Research Service, Research Branch, Agriculture Canada, has a remote sensing program which includes nine goals. To develop the theoretical basis and a catalog of spectral signatures for the application of infrared and other remote sensing techniques, to make non-destructive, instantaneous measurements of biological parameters through the development of sensors, techniques and systems to solve specific problems for Branch establishments, and to provide a resource of information and techniques for use as ground truth data in remote sensing of agricultural parameters and develop a ground truth station to compliment satellite and aircraft sensors. This program is also co-ordinated with the Agriculture Working Group of the Canadian Advisory Committee of Remote Sensing.

This report deals with the research and development accomplished since the second meeting (October 1973) of the Agricultural Working Group. They are a continuation of the development of a system:

a) For objectively measuring the yield of experimental cereal plots.

b) For the detection of disease in experimental crops.

c) To identify parameter changes within the same specimen.

d) To develop an open path CO_2 analyzer.

e) To develop a laser fluorometry system.

f) To measure the optical characteristics of soil and find out the influence of soil spectral properties on the measurement of crop yield and disease.

1.0 INTRODUCTION

Electro optical instruments are being developed to measure incoming and reflected radiant energy, the reflectance, absorption and transmittance properties of plants and soil, the reaction of plants to different portions of the wavelength spectrum and measure the influence of light energy "$h\nu$" in the over-all process of photosynthesis which is expressed as:

$$6CO_2 + 6H_2O + nh\nu \rightarrow C_6H_{12}O_6 + 6O_2$$

A logical step was to extend the work to instruments which measure optical characteristics such as absorption, reflectance, transmission and fluorescence of plants when harvested or in a non-destructive mode on standing crops.

It is well known that every object, living or dead, absorbs, reflects or transmits some portion of the radiant energy with which it comes in contact, or fluoresces at some wavelength which exits from the plant molecules. Before expanding further into the development of electro optical instruments to measure these characteristics, an examination of the basics of what is to be measured and the most useful portion of the optical spectrum for such investigations was examined. As a result investigative effort was concentrated on the following fields:

a) Crop yield per acre prediction in breeding research

   Plant breeders need to predict, at an early stage of the crop growth, the yield of a particular variety at maturity under average environmental conditions. This would allow seeding of experimental crops two or three times in the same growth season.

b) Early disease warning

   Plant pathologists and farmers are constantly combating disease. They spray the crop with insecticide whether the crop is healthy or diseased. In fact the farmer is using "preventive medicine" to protect his crop which is costly. Therefore, farmers and plant pathologists need an early disease warning capability which will indicate when the crop is infected so that action can then be taken.

c) Accurate crop yield estimation

Accurate estimate of yield per acre of crops on a daily basis would enhance proper pricing of agricultural commodities. The statistician and economists in agriculture could establish realistic policies relating to supply and demand.

Before establishing yield, identification of the crop with reasonable accuracy must be resolved. Identification of varieties within a crop presents immense problems.

To measure yield in a crop, it is necessary to know which constituents of the crop and the wavelength in the optical spectrum that indicates "changes" which can be attributed or translated into yield data.

Laboratory spectroscopy experiments indicate that the most suitable spectrum for yield estimation and disease detection is the infrared (IR) range from 0.72 μ to 6 μ. Also the wavelengths covering the green and red chlorophyll and the near IR range (550, 680, 730 nm) may aid greatly to yield estimation. The ultra violet (UV) 250 - 400 nm range may be helpful in variety identification within one crop, and in disease detection.

The measurement of CO_2 uptake or release by a growing plant, may be helpful to estimate yield for a variety of agricultural plants.

2.0 INSTRUMENTATION

The development of a mobile laboratory system began in 1971 to estimate yield and early disease detection. In preliminary investigations it has been found that when estimating yield or detecting disease, the effect of environmental changes on the reflectance properties of plants must be known. Reflectance characteristics of plants vary with their morphology and pigmentation which may be affected by disease, nutritional levels, stage of maturation and soil conditions. Taking all this into consideration, it was decided that the system must include the following instrumentation.

Spectrophotometer: To measure optical properties of agricultural plants and products.

Radiant energy meter: To measure the total available (net, incident, soil radiated) energy reaching the plant.

Temperature measuring equipment: To measure the soil temperature, above the soil, at various heights in the plant canopy and ambient temperature.

Humidity indicating instrument: To measure the humidity in the environment of the plant, and also to measure the wetness of the plant surface.

Windspeed: To measure the velocity of the wind at the plant level and its direction.

Heliostat: To measure the sun angle when spectral measurements are taken.

All the above instruments are interfaced to a PDP-11 computer (Fig. 1). A view of the spectrophotometer is shown (Fig. 2).

The telescope (b) (EG&G Model 585-36, Salem, Mass.) looks at the plants with a maximum field of view of 2^{o} and directs the reflected energy into a monochromator (a) (McPherson Model 2051, Acton, Mass.). The monochromatic spectral energy is sensed by a detector (c). Detectors are used according to the spectral range to be covered and the amount of available reflected radiant energy. For the spectral range of 0.3 - 1.0 μ an enhanced UV response photovoltaic silicon photodiode (EG&G No. UV-100) is used. The NEP value of the detector is greater than 10^{-13}W and its responsivity is greater than 10^{7}V/W. For the range of 1 - 2.6 μ an air cooled lead sulphide (PbS) photoconductive cell (Mullard 62SV) is used, with a NEP value of 10^{-10}W, and responsivity of 300 μV/μW. An indium antimonide (InSb) photovoltaic detector (Barnes Eng. InSb A10) with a saphire window is used for the spectral range 2.5 - 4.5 μ. Its NEP value is 10^{-9}W. For NEP values of

5.10^{-8} or when the reflected signal is small a ferro electric detector (Laser Precision Corp. Model KT-4010) is used which covers the spectral range for 0.4 - 60 μ.

The output of the detector is processed and amplified by the amplifier (d). The amplifier ouput is fed to the computer (f) and to an analog recorder (e). The grating of the monochromator is rotated by a synchronous motor and drive mechanism and the rate of wavelength scan can be selected from 12 available speeds from 0.5 - 2000 Å/min (h). The wavelength drive shaft is used for automatic wavelength encoding. The encoder (Electronic Resources Counter Product, Division of Tasker Industries, Los Angeles, Calif.) is a 5-digit bi-directional 15,000 counts per minute shaft driven mechanical counter with built in digital output switches on each digit. These switches are connected to the interface unit.

The hardware interface (Fig. 3) is built on five boards; one board being a 5 V dc power supply. The wires from the encoder are brought into the interface unit by a 42 wire cable through connector A. Only the four higher digits (10; 100; 1,000; and 10,000) from the wavelength drive are brought into the interface, since the spectral resolution required does not exceed 10 Å. The wires coming from the 10 and 100 digits of the encoder switches are connected to board 1, and from switches of 1,000 and 10,000 digits are connected to board 2. The four centers of the switches are grounded. The position of the encoder switch is decimal to BCD converted by a resistor and IN914 diode decoder network.

The BCD signal levels of the converter output are inverted to satisfy the operating conditions of the DR11-B, the direct memory access interface of the computer. The inverters (RCA CD2310E) (located on board 3)

also serve as buffers to compensate losses due to cable length from the encoder. Four inverters are assigned to each BCD converter, except the 10,000 digit where there are only three, since the highest wavelength to be used is 79,999 A. A cycle set circuit (on board 4) instructs the DR11-B when the memory should accept or read the incoming data.

The software interfaces the wavelength position with the spectral reading of the detector as well as performing arithmetic calculations. The flow chart used to interface the wavelength drive with the spectral readings is shown in Fig. 4 (a). After the teletype (TTY) has printed out the wavelength and output headings, the software program initiates and sets up the bus address and word count registers, it issues a GO pulse by loading a bit Ø of status register DRST. GO clears the DR11-B READY bit, and direct memory access DMA operation begins. The wavelength number from the encoder is brought in through the interface, its BCD values are converted to ASC11 and printed under the heading of WAVELENGTH. The software jumps to subroutine loop 1 to pick and initialize the channel and gain pointers (Fig. 4 (b)). The next subroutine loop 2 (Fig. 4 (c)) then brings in the spectral reading, picks up gain, exponent and scale factors, converts and assigns sign and decimal place, performs BCD to octal to ASC11 conversion, and prints out the spectral data under the heading OUTPUT.

The computer is programmed to take readings each day from 6:00 to 20:00 hours at 30 minute intervals. At the start of each day the date is printed out. At the start of each set of data the time, humidity, ambient temperature, temperatures at different points in the crop canopy, crop height, and soil moisture and printed out (Table 1). At each individual point the wavelength, spectral data, ambient radiant energy and wind speed is printed.

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It has been found necessary to take radiant energy and wind speed readings at each spectral data point since these parameters change rapidly due to cloud movement and wind speed variations. The instruments measuring environmental characteristics are standard equipment except the heliostat which was developed for the purpose. The analog data is converted by an A/D convertor multiple and fed to the computer. The whole system is assembled in a mobile laboratory (trailer).

2.1 OPEN PATH CO_2 MEASUREMENT - TO ESTIMATE YIELD

Laboratory investigations were performed to examine the possibility to use the plants carbon dioxide uptake as a measure of yield estimation. The encouraging results initiated a development to measure carbon dioxide (CO_2) with an open path CO_2 analyzer. It has been established that 50% of CO_2 uptake by plants is converted to dry matter gain. Therefore, if this uptake can be measured accurately, a form of yield estimation will be available. Figure 5 gives an outline of the instrument.

The photosynthesis equation;

$$6CO_2 + 6H_2O + nh\nu \rightarrow C_6H_{12}O_6 + 6O_2$$

indicates that when stimulated by the photon $h\nu$, the plant converts the CO_2 uptake using the H_2O available to organic matter n (CH_2O) and oxygen.

The carbon content of CH_2O is

$$C_c = \frac{C}{CH_2O} = \frac{12.011}{30.024} = 40\%$$

If a growth rate of a plant is measured W = 100g m^{-2} day^{-1}, then the CO_2 uptake, or the amount of CO_2 assimilated by the plant, is calculted.

$$T_{CO_2} = W.\ C_c.\ (CO_2)_c = 100 \times 0.4 \times 3.664 = 146.56g\ m^{-2}\ day^{-1}$$

where $(CO_2)_c = \frac{C + O_2}{C} = \frac{12.011 + 31.998}{12.011} = 3.664$

Since the assimilation of CO_2 by the plant occurs during the day over say 12 hours, the average CO_2 uptake per sec. will be

$$\frac{W}{h.60.60} = \frac{146.56}{12.60.60} = \frac{146.56}{43.200} = 3.39.10^{-3} \text{ g m}^{-2} \text{ sec}^{-1}$$

2.02 OAT VARIETY IDENTIFICATION

As with many technologies, "spin offs" are developed sooner than the "original objectives". Our objective is to measure yield of various grain products. This required differentiation between different grain plants (oat, wheat, barley etc.), and also to find out which part (seed, leaf) of the plant will be the "tell tale" for yield estimation. Taxanomists have the problem of classification and identification of varieties within a crop such as oats or wheat. Research was directed to determine if there are significant differences in optical properties within the varieties so that they can be identified. Since the system to measure spectral properties of leaf was available, all that was needed was an optical reflectance attachment for seed samples (Fig. 6). The operation of the equipment is self explanatory.

Samples of different varieties of oats (Dorval, Garry, Sioux, Harmon, Random, Rodney, etc.) were placed in the sample holder, in hulled, dehulled and ground condition, and spectral measurements taken. The spectral curves resemble seeds with protein, oil moisture and carbohydrate contents. Figure 7 presents the spectral curves of 5 oat varieties, one rye and one wheat. There is a definite difference between wheat or oats, but it is hard to make a qualitative difference between oat varieties. Very little wavelength differentiation is available, but there are differences in amplitude at points in the spectrum which indicate the possibility to measure protein, fat and moisture content of grains and possibly do this on a standing crop which can then be correlated to yield by infrared spectral measurements.

In search for better identification of varieties within one crop fluorescence spectrocopy was used. The fluorescence spectrograph developed consists (Fig. 8) of an exitation source (I) with a light collimator (M_{EF}), optical filter (F), sample holder (S_h), focusing mirror (M_{sf}), monochromator with the appropriate mirrors (Mc, M_f), grating (G) and slits (S, S_o), a detector (PM) and a readout system (R). Fig. 9 shows the emission curves of six oat cultivars, which indicates an improved discrimination in the amplitudes of different cultivars. The samples were exited with a 2400 $\mathring{A}$ wavelength energy. Total number of measurement of each of the six cultivars was 150. Table 2 gives the mean, maximum and minimum readings of the peaks and valleys of each cultivar. The data clearly indicated that only P_1 and P_2 discriminated between cultivars at a level adequate for identification purposes. While there were overlaps in individual P_1 values, the means were far from each other. Table 2 and Fig. 10 provide a crude scale for identification between the six oat cultivars. This development is considered a break through in identification of varieties within a cereal crop and is a helpful tool for plant breeders, seed lot operators, seed dealers and farmers, and food processors and with further development hopefully for remote sensing applications.

3.0 INSTRUMENTATION UNDER DEVELOPMENT

3.1 Laser exited fluorescence spectroscopy

A nitrogen laser (3371$\mathring{A}$) with dye pump and optics has been acquired from Laser Energy Inc. (Rochester, New York, N.Y.). Several lasers from different manufacturers were considered. Laser Energy Inc., Model 337 dye laser system, Table 3, complete with N2-50 sealed nitrogen laser, control module power supply, No. 337 dye laser head, and control module including circulatory pump, filter and thermoelectric cooling, were chosen for the following reasons:

(a) It does not need water cooling

(b) It does not need nitrogen gas bottles, pump, etc.

(c) It is a longitudinal pumped laser system, as a result the output beam is only 3 mm diameter, and the beam divergence is 3m rad.

(d) It was the most competetive in price and has the same technical performance as several competitors.

We have used the laser for 60 hours without laser tube breakdown.

The dye laser system is intended to be used for reflectance measurement of agricultural plants at night when the background noise due to the sun is absent. It will be used for fluorescence measurement on standing crops, for crop identification and disease detection purposes.

3.2 LEAF COVERAGE RATIO METER

Agro-spectroscopists have found that the reflectance ratio of the green chlorophyll 5500 $\mathring{A}$ and the red chlorophyll 6750 $\mathring{A}$ as well as 7320 $\mathring{A}$ in the near IR closely correlates to the leaf coverage of the crops which can be related to yield, especially on forage crops.

A ratio meter under development will have the capability to measure the ratio of the incoming energy impinging on to the plant and correct the measured ratio from the plant accordingly. The meter will have to measure the ratio over different time durations (1 min, 3 min, etc.). The meter will indicate each wavelength reading and its ratio in digital form, it will have a BCD output and interface for a tape punch drive.

3.3 RAPID-SCAN SPECTROMETER SYSTEM EVALUATION

Tektronix Inc. developed a rapid-scan spectrometer (RSS) with an electronically scanned image detector. The characteristics are given in the Tektronics operators instruction literature (Tektronic, 070-1641-00) Table 4

Wheat and barley plants were tested using the following procedure. The plant was irradiated by a tungsten lamp from 1.5 meters. Before each spectral measurement the RSS were calibrated to zero by placing a shutter at the entrance. One hundred and twenty-eight readings were taken, and the values (Fig. 11a) stored in a memory of the RSS system. The shutter was then removed and an optical white standard was placed before the plant and 128 reading of its reflectance value (Fig. 11b) stored in the memory. The reflected energy from the plant was then measured 128 times and these values (Fig. 11c) stored in the memory. Instantly the corrected reflectance curve was displayed on the CRT of the oscilloscope and a hard copy a half a minute later (Fig. 11d).

The resolution of the RSS for spectral measurement of plants needs improvement but it seems that it has great possibilities in remote sensing, especially in ground truthing.

3.4 SOIL REFLECTANCE MEASUREMENT

Using the spectrometer shown in figure 6, spectral curves of different kinds of soil were taken. The identity and characteristics of the soils are given in Table 5. The following spectral ranges were covered 450 - 1000 nm, 1.0 - 2 μ, 3 - 5.5 μ. The 2 to 3 μ range was not covered due to grating inefficiency on this range. The detector used for the range 450 - 1000 nm was a silicon photodiode (EG&G No. UV-100) and for ranges 1.0 - 2 μ and 3.0 - 5.5 μ

an indium antimonide InSb photovoltaic detector. Figure 12 gives the spectral curves of soils. In the 450 nm to 1 μ spectral range, the glass bead gives the highest reflectance and has a spectral response in the visable range. The lowest reflectance given in this range was from the rideau clay loam, having a relatively flat spectral response through the whole range. As a comparison, the reflectance curve of an Ivy leaf in this range is also given which shows a spectral response in the 480 - 530 nm and in the 630 - 530 nm band, a higher reflectance in the 550 nm region and the highest reflectance in the near infrared region.

In the 1 - 2 μ spectral range, montmorillamite clay gave the highest reflectance with a relative output of 75%, and the glass bead gave the lowest reflectance with a relative output of 20%. All the soils gave a relatively flat spectral response in this range.

In the 3 - 5.5 μ spectral range, again montmorillamite clay had the highest reflectance with a relative output of 35%, and uplands loamy sand showed the smallest reflectance with a relative output of 17%. The montmorillamite clay has several absorbency peaks, the highest at 3.9 μ and smaller peaks at 4.3 μ and 4.5 μ which suggest some unique characteristics for that soil. Some of the other soils show small absorptions but in general they have quite a flat spectral curve.

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Table 1. Computer print-out

July 28/71
Time 0600

H%	T(AB)C	T(P1)C	T(P2)C
30.835	23.560	21.436	18.823
M%	**L(M)**	**R(GC)**	**WS(M/H)**
28.101	1.2036		
W(A)	**P(RO)MV**		
	12.257	0.2027	2.3829
200	12.159	0.2027	2.3853
400	12.524	0.2076	2.3853
600	14.429	0.2076	2.3853
800	15.161	0.2076	2.3853
6000	17.921	0.2101	2.3853
200	20.313	0.2101	2.3927
400	20.508	0.2125	2.3927
600	11.280	0.2027	2.3878
800	11.085	0.2003	2.3878
33000	11.085	0.2003	2.3878
200	11.085	0.2003	2.3878
400	11.086	0.2003	2.3878

H% = humidity

T(AB)C = ambient temperature

T(P1)C, T(P2)C = temperatures in crop canopy

M% = soil moisture

L(M) = height of crop

W(A) = wavelength

P(RO)MV = reflected energy

R(GC) = radiant energy

WS(MF) = wind speed

Table 2. Peak and valley values for the six oat cultivars tested (note V_4 was not significant) based on 100 samples of each cultivar.

Cultivar		P1	P2	P3	P4	V1	V2	V3
Sioux	Maximum	92	41	51		38	39	
	Mean	90	40	50.5	24	37	38	29
	Minimum	85	39	49.5		36	37	
Garry	Maximum	88	40	51.5		36	38	
	Mean	83	39	50.5	25	35	37.5	27
	Minimum	79	38.5	50		34.5	37	
Rodney	Maximum	75.5	39	48		35	47.5	
	Mean	70	37	47	23.5	33	45.5	26
	Minimum	64.5	35	45.5		31	44	
Harmon	Maximum	69	35	46		30.5	33.5	
	Mean	64	34	45	22	29	33	25
	Minimum	61	32	43		28	31	
Dorval	Maximum	60	36.0	47		30	33.5	
	Mean	58	35	45	23.5	30.5	34	26.5
	Minimum	57	34.5	44		31.5	35.5	
Random	Maximum	54	33	43		27	32	
	Mean	50	31	40.5	20	25.5	30.5	22.5
	Minimum	47	30	39.5		24	30	

Table 3. Specifications for N2-50 Laser head and 337 dye and pump system.

Specifications:
N2-50

Wavelength	337.1
Bandwidth	0.1
Peak Power	2-50 KW Adjustable
Energy per Pulse	200 microjoules typical
Average Power	20 milliwatts at max. rep. rate
Repetition Rate	1-100 Hz
Pulse Width	10 Nanoseconds
Beam Diameter at $1/e^2$ Points	3 mm
Beam Divergence	3 milliradians
Amplitude Stability	3 percent
Jitter Stability	Within 2 nanoseconds
Power Requirements	117 V AC, 60 Hz

System 337

Tuning range - Option 01 370-460 nm
Option 02 420-520 nm
Option 03 520-650 nm
Output-utilizing the N2-50 Pump Laser at Dye peak

Option	Peak Power Kilowatts	Energy per pulse microjoules
01	4	50
02	4	50
03	7	90

Beam diameter at $1/e^2$ points	1 mm
Beam divergence	1 mr
Line width	3 nm
Line width with etalon	0.1 nm typical
Power requirements	115 AC
Pulse width	10 nanoseconds
Repetition rate utilizing the N2-50 pump laser	1-100 Hz

Table 4. Characteristics of rapid scanning spectrometer

The J20/7J20 Rapid-Scanning Spectrometer functions as a rapid electronically-scanned spectrometer optimized for kinetic studies, and also as a general purpose analytical instrument with features new to spectroscopic instrumentation. The following discussions briefly outline details of instrument operation and some of the operational trade-offs to be considered when using the spectrometer.

The spectrometer system can electronically scan a 400 nm (4000 angstroms) segment of the spectrum (using Grating A) in less than 10 ms. This wide range is useful for obtaining an overview of the spectrum. For detailed analysis, an approximately 40 nm segment can be scanned (using Grating B) with resolution of at least 0.4 nm (4 angstroms) in first order. The 40 nm scanned segment can be continuously varied over the spectral range of 300 nm to 1100 nm (first order). Variable scan rates allow slow scanning modes with integration of up to one second (for scanning low light-level spectra) without using digital techniques.

The output spectral display on the crt can be automatically corrected for the spectral response of the optical system and detector. Automatic spectral correction can also be made for external optical devices such as light sources, filters, collection optics, etc. Absorption measurements made in this manner do not require dual-beam techniques. In addition, the instrument is radiometrically calibrated; therefore, direct real-time measurements of spectral radiant power are possible with this instrument. Figure 4 shows a spectrum containing the 365 nm Mercury triplet as it appears in the display on the oscilloscope crt. Note that the important scale factors such as spectral power, scan time, marker wavelength, and wavelength span appear in the crt display along with the scanned spectrum. The intensified wavelength marker spot can be moved horizontally across the displayed spectrum by rotating the front panel MARKER control

The Czerny-Turner grating spectrometer provides high through-put, coma correction, and is nonvignetting. Nonvignetting means that every point in the entrance slit (even top and bottom) will accept the full f/6.3 aperture. This is essential to making accurate radiometric measurements. As a point of reference, if this system were specified in the often used manner of focal length divided by the diameter of the entrance mirror, it would be an f/3.8 system.

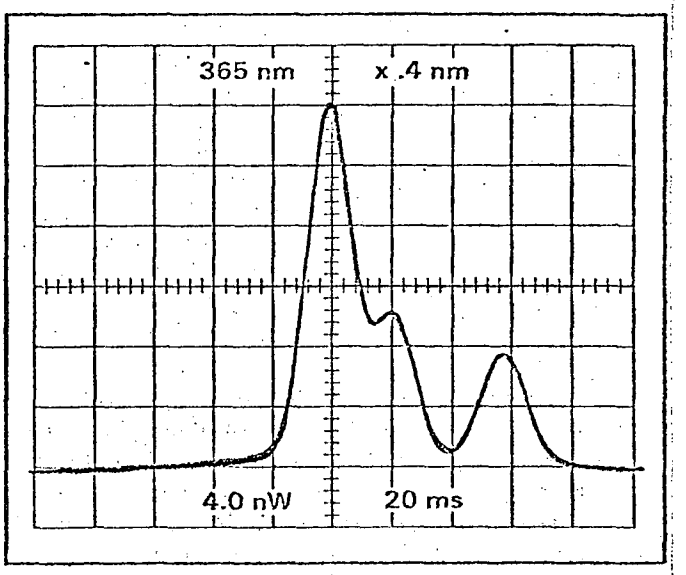

Fig. 4. Spectrum display of 365 nanometer mercury triplet.

In lieu of an exit slit, the spectrometer images the dispersed spectrum onto the target of a vidicon image tube. The photosensitive target of the vidicon consists of an array of photodiodes on a silicon substrate. Incident photons are absorbed into the silicon substrate, creating hole-electron pairs. Absorption of ultraviolet light occurs near the surface of the silicon, while infrared penetrates deeply before being absorbed. The holes, which are minority carriers, diffuse into the space charge field and are immediately swept across the photodiode junction into the p-type region. The p-type region, which had been charged by a previous scan of an electron beam, is discharged proportionally to the number of photon-induced holes. When the scanning beam again sweeps the region, it will have to supply current to recharge the diode. This current flow is thus proportional to the number of photons incident on the vidicon target and becomes the video signal.

Table 5. Spectral curves of different soils

Soil type	Wilting point % atmosphere	Field capacity % 1/3 atmosph.	Loss of ignition %	Sand % 70.05 mm	Silt %	Clay % >>0.002 mm
Montmorillamite clay	<20	<40	0	0	0	100
Rideau clay loam	13.3	29.2	7.6	32	40	27
Gremville loam	8.5	18.9	7.3	43	39	11
Uplands loamy sand	5.9	11.7	5.0	78	13	8
Glass beads 29 µ	>>1.0	>>5.0	0	100	0	0

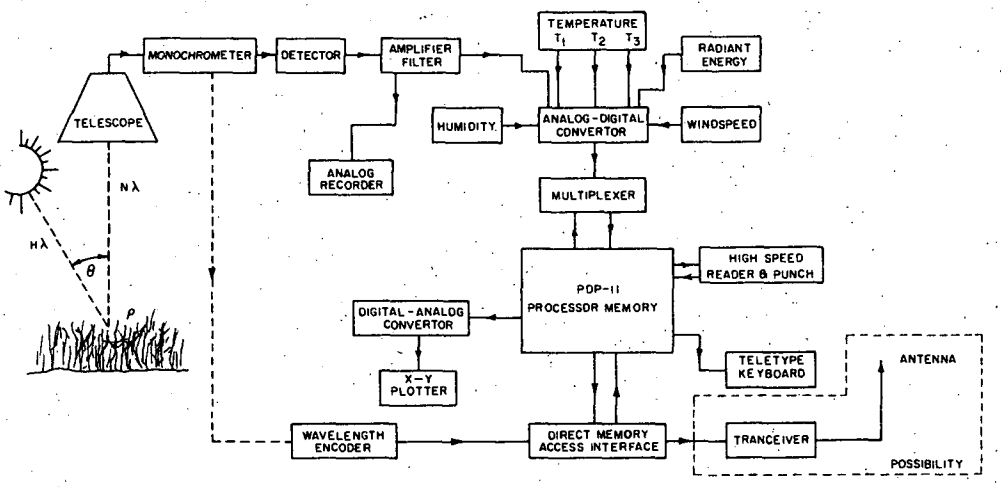

Figure 1. Block diagram of reflectance measuring system.

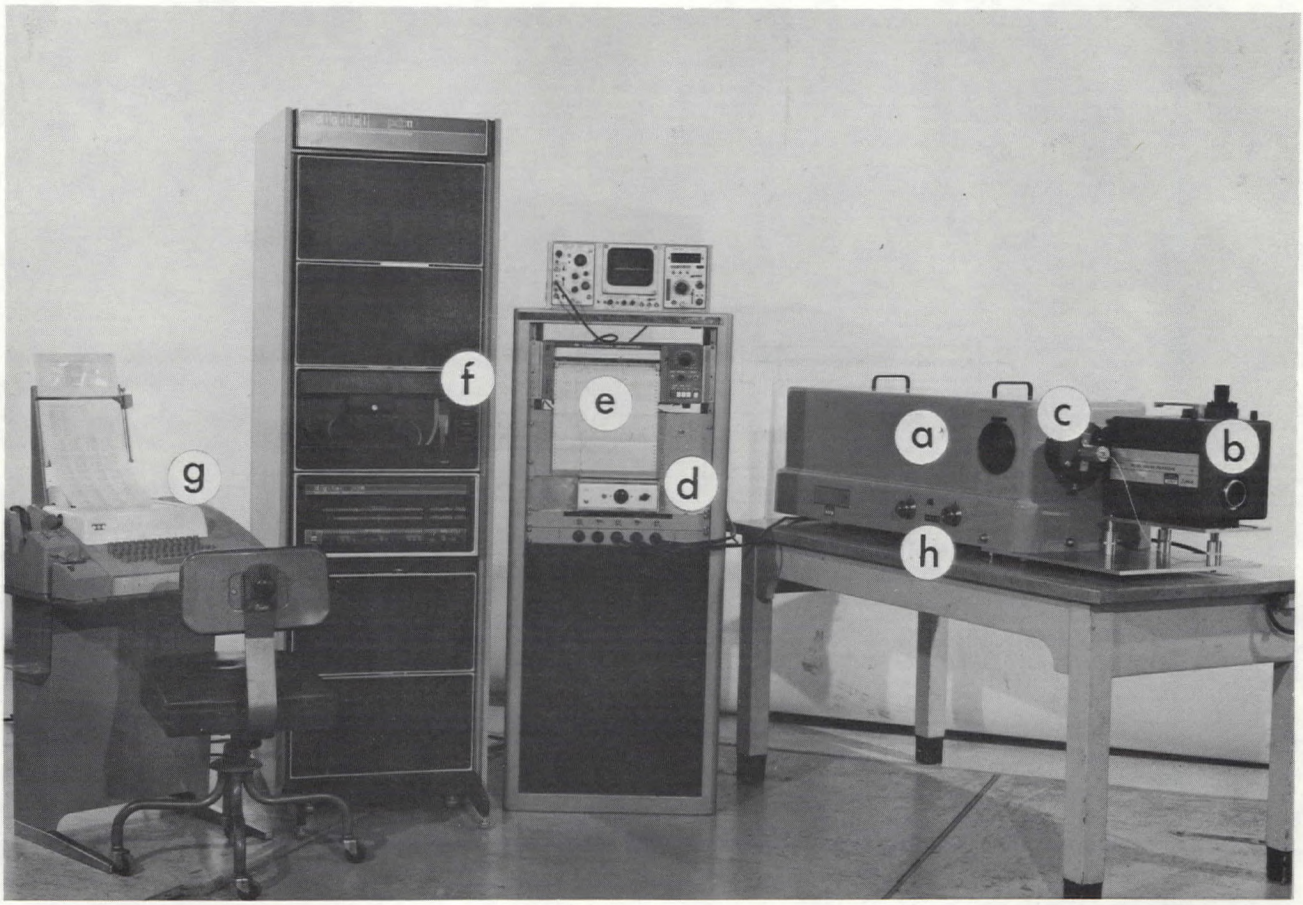

Figure 2. Pictorial view of spectro photometers system. a. monochromator, b. telescope, c. detector, d. electronic amplifier and signal processor, e. analog-recorder, f. digital computor, g. teletype printout, h. wavelength drive.

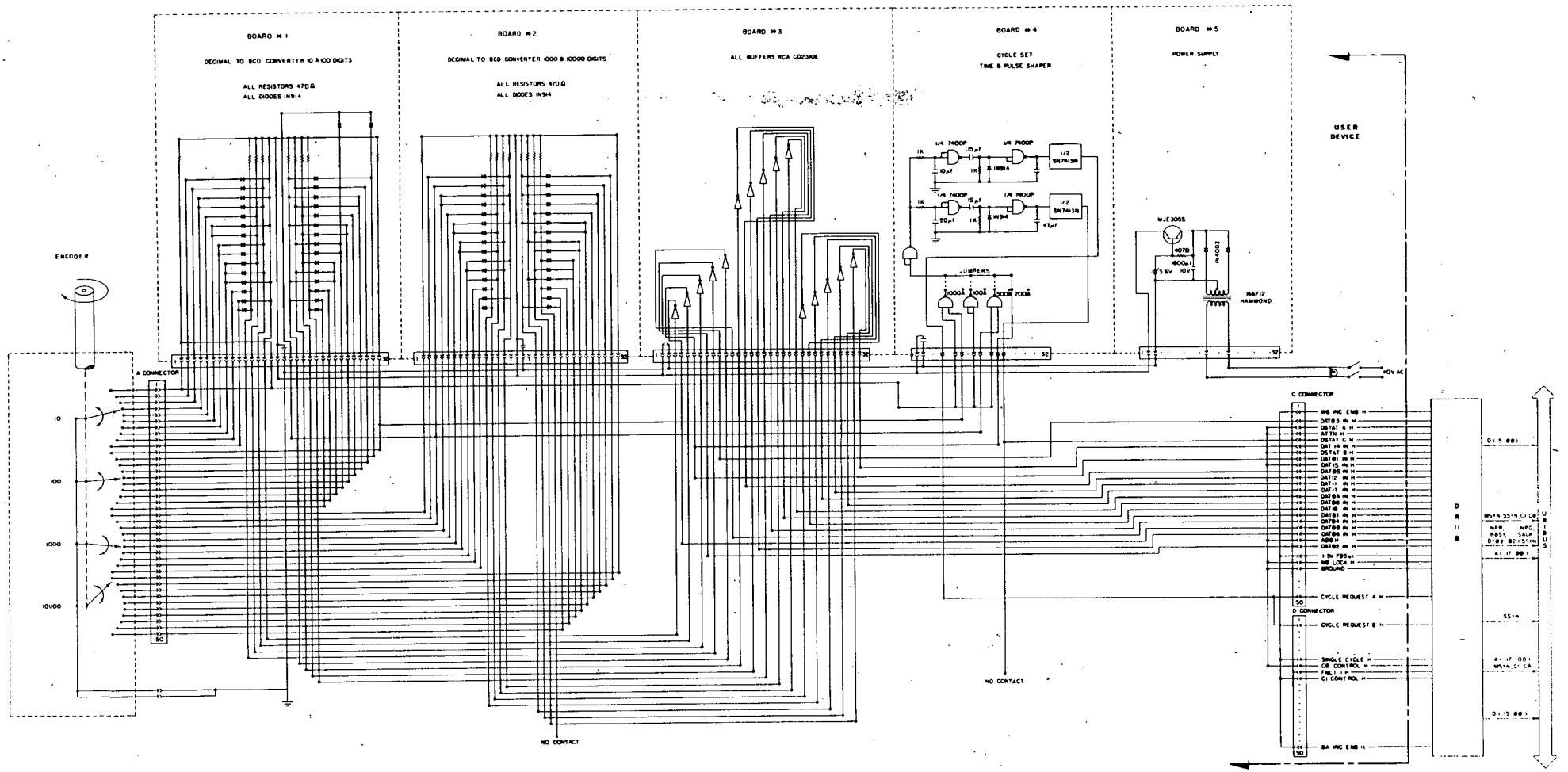

Figure 3. Wiring diagram of hardware interface unit.

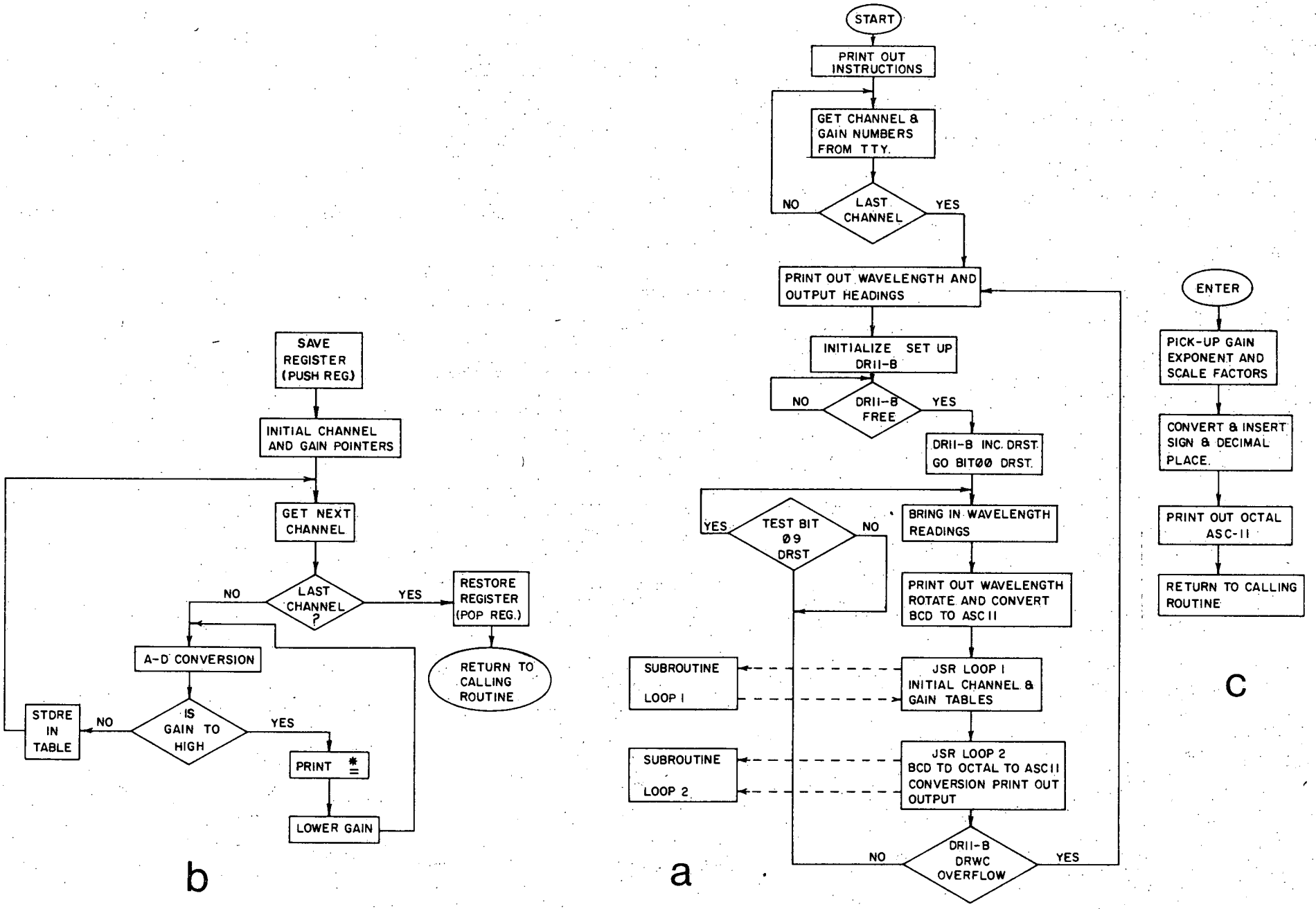

Figure 4. a. Flowchart of software interface, b. Flowchart of subroutine loop 1, c. of subroutine loop 2.

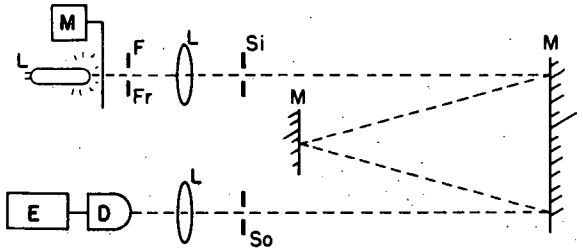

Figure 5. Schematic diagram of open path CO_2 analyzer. L lamp, M_r motor chopper, F, F_r interferance filters, L focusing lens, M front surfaced flat mirror, S_i, S_o input and output slits, D detector, E electronic circuitry.

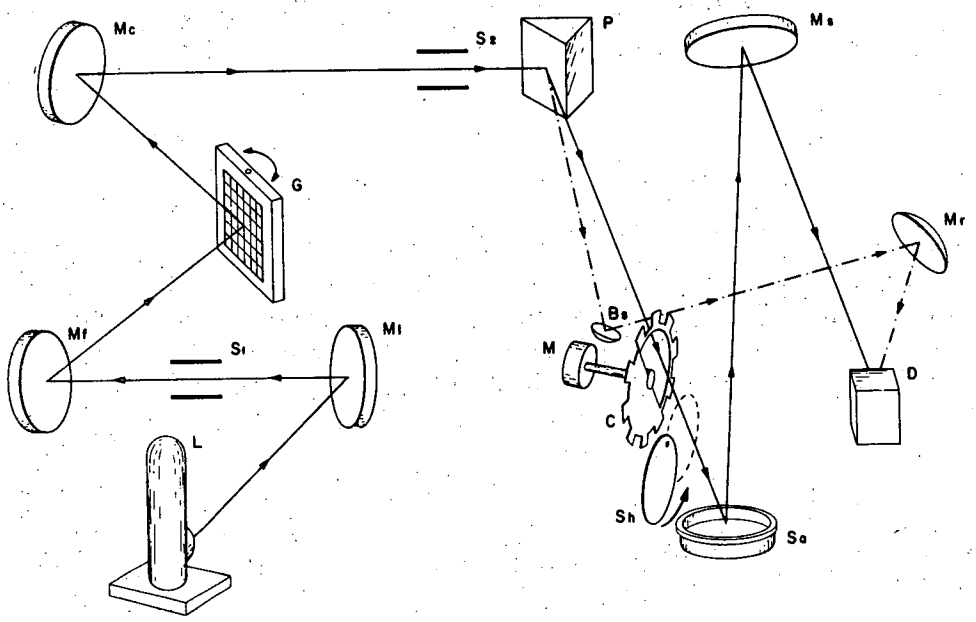

Figure 6. Optical path for reflectance attachment. L light source, M, M_r, M_c front surface concave mirror for incident path, M_s M_r front surface concave mirrors for reflectance path, P front surface flat mirror, B_s beam splitter, S_1 S_2 input output slits, G grating, M motor, C chopper, S_a sample holder, S_h shutter, D detector.

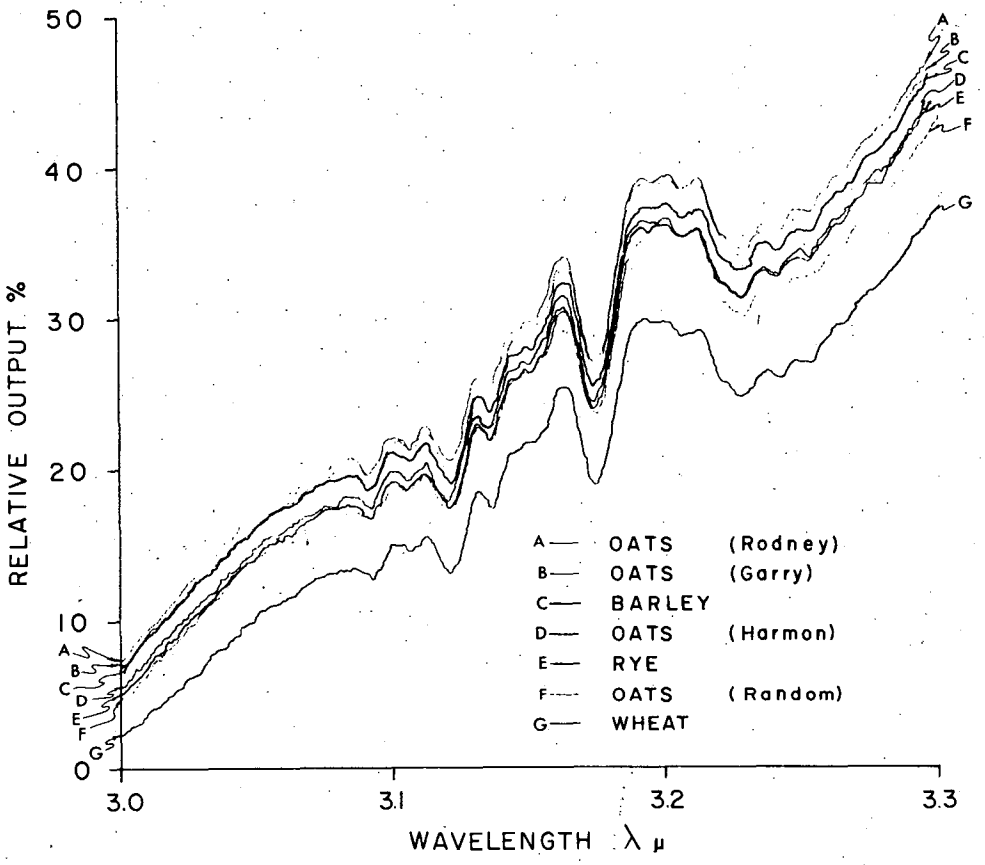

Figure 7. Reflectance curves of different grains.

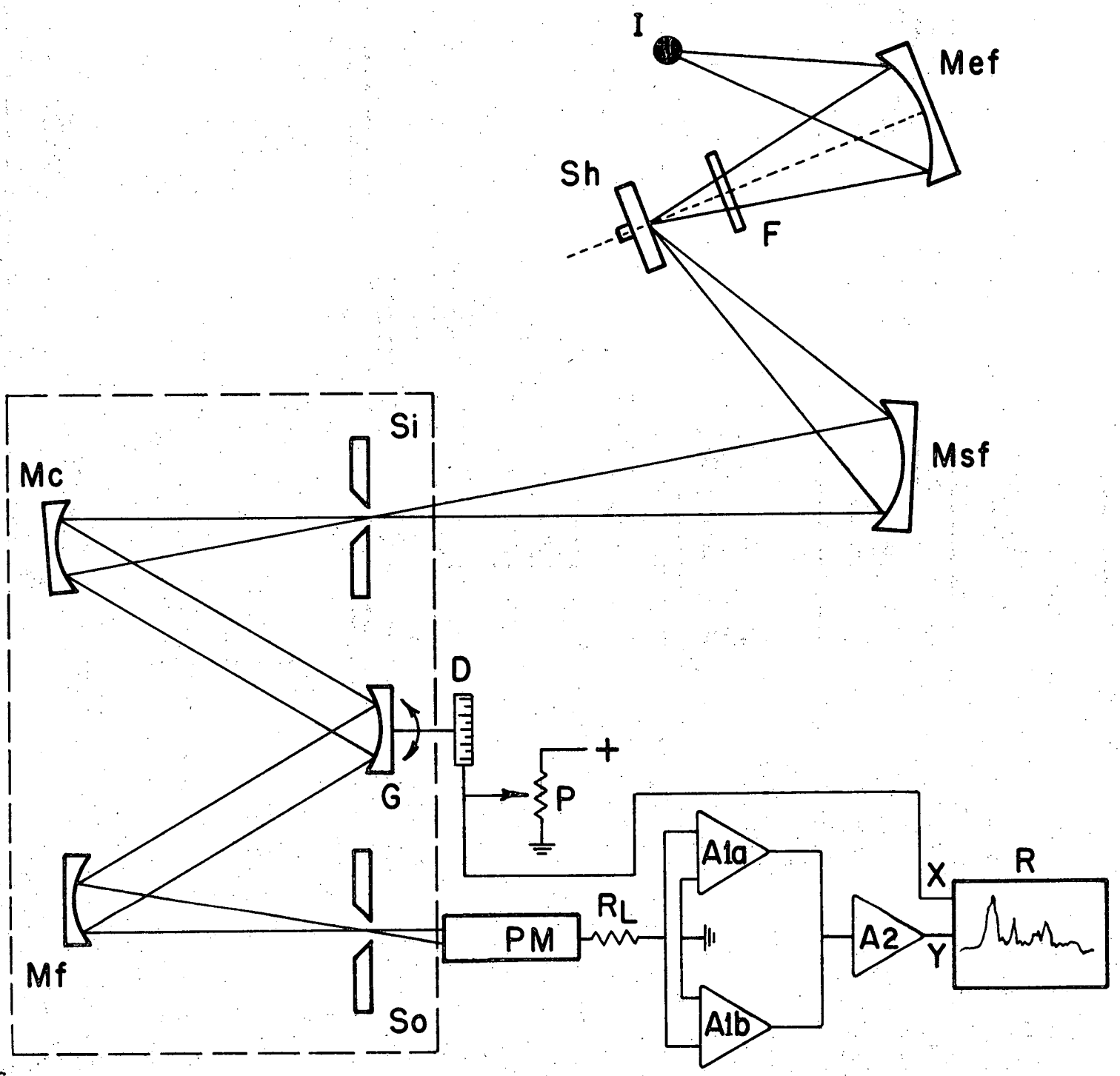

Figure 8. Schematic of fluorescence spectrograph. A_{1a}, A_{1b}, A_2 operational amplifiers. D wavelength drive. F interference filter. G grating. I exitation source. M_c, M_f, M_{ef}, M_{sf}, focusing and collimating mirrors. P potentiometer. PM photo-multiplier. R_L load resistor. R recorder. S_h sample holder.

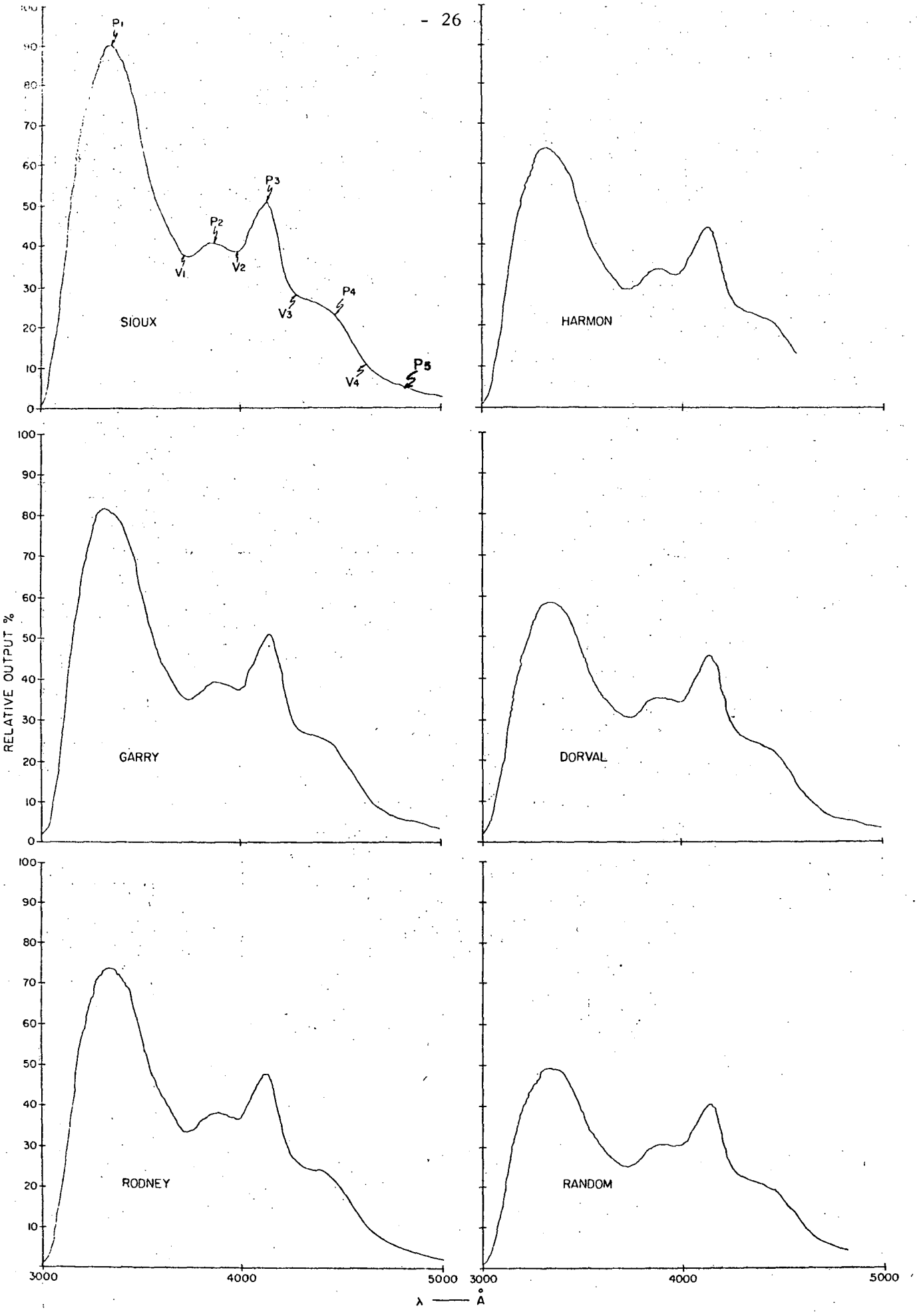

Figure 9. Emission curves of six oat cultivars. P_1 - P_5 peak points, V_1 - V_4 valley point selected to evaluate identities of oat cultivar.

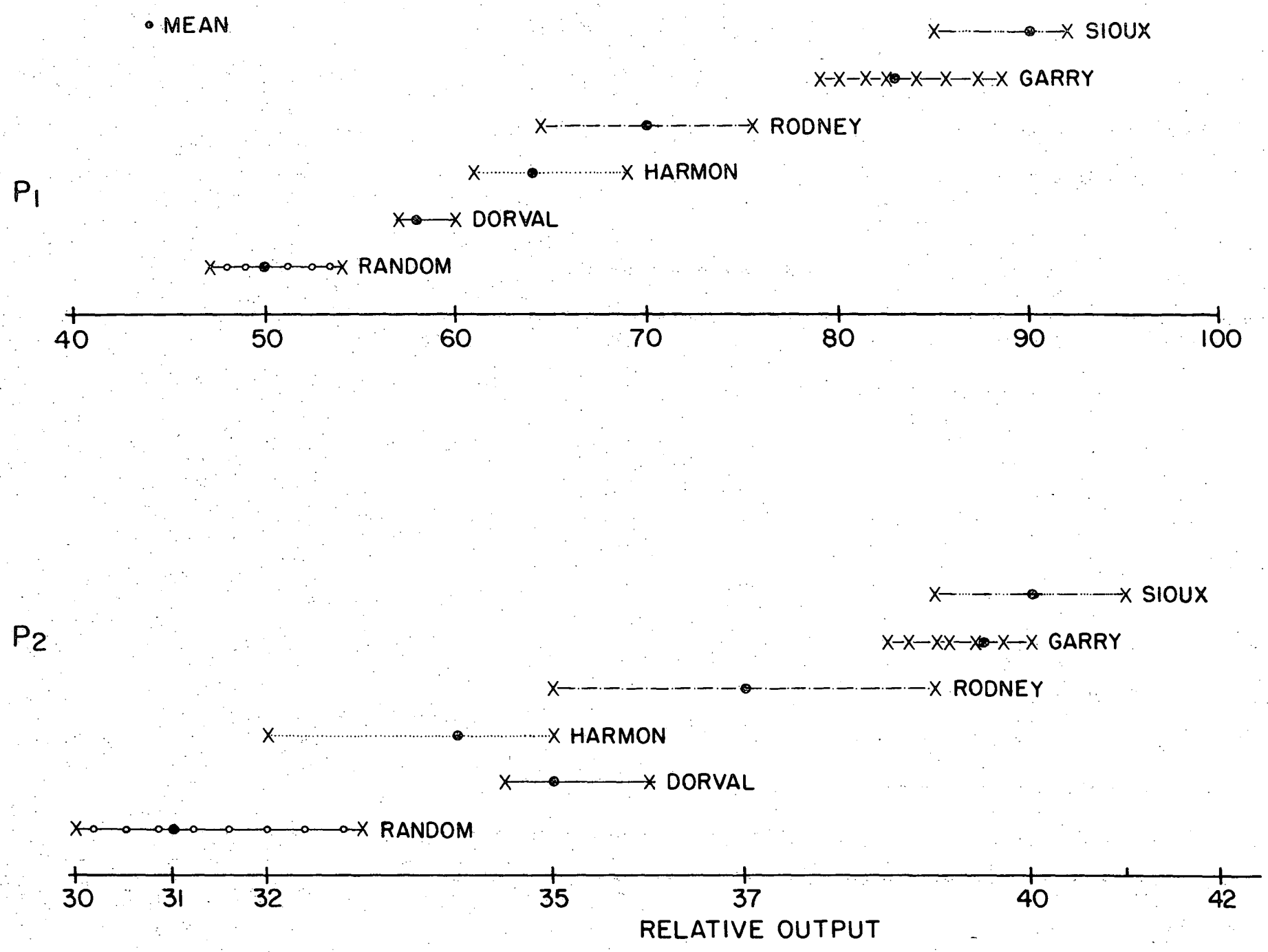

Figure 10. Crude identification scale of six oat cultivars. P_1 amplitude of the first peak, P_2 amplitude of the second peak of the emission curve.

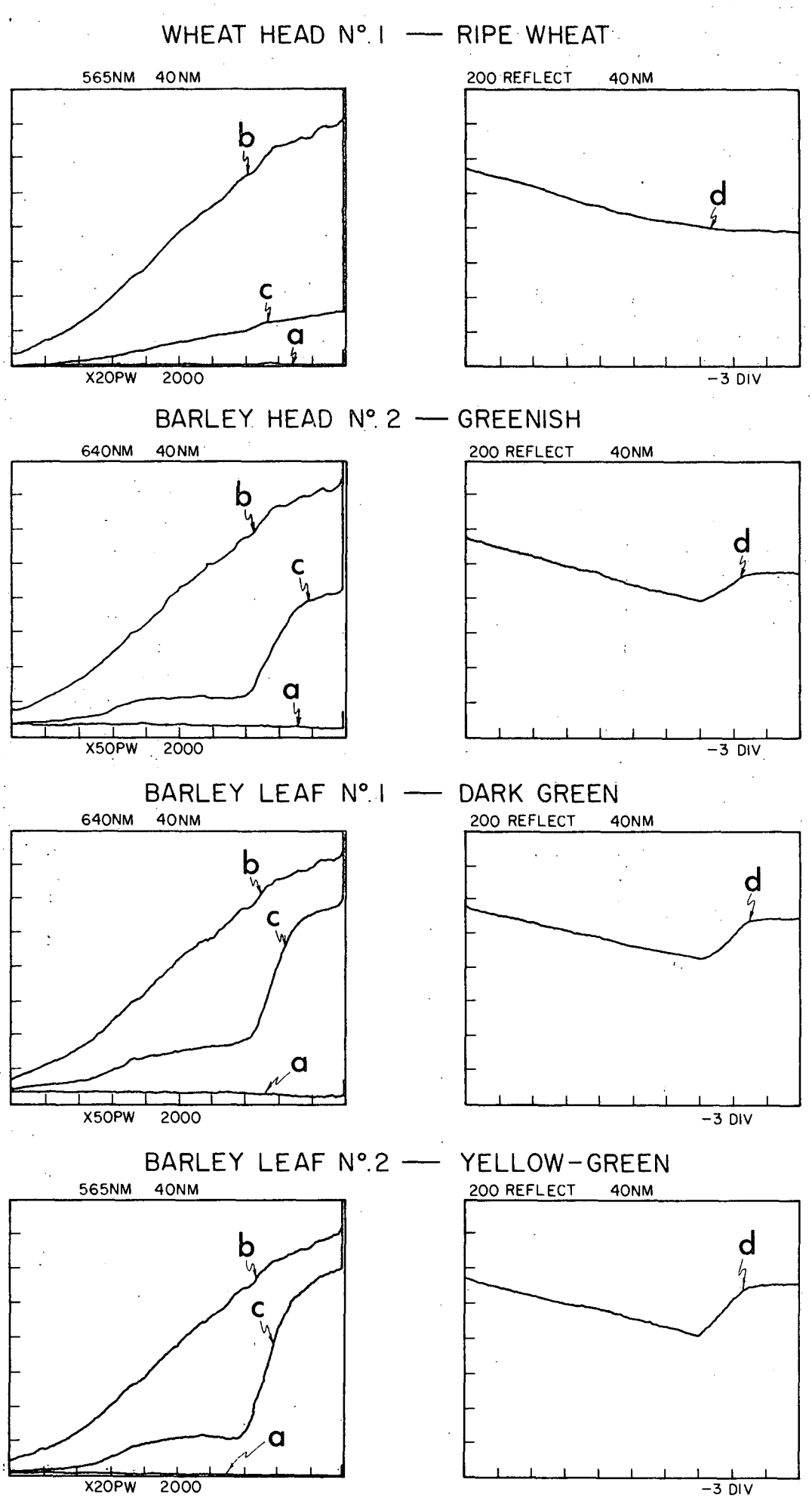

Figure 11. Spectral curves of wheat and barley head and leaf with the Tektronix rapid scan spectrometer. a. baseline; b. spectral curve of Kodak white standard; c. spectral curve of plant; d. corrected spectral curve.

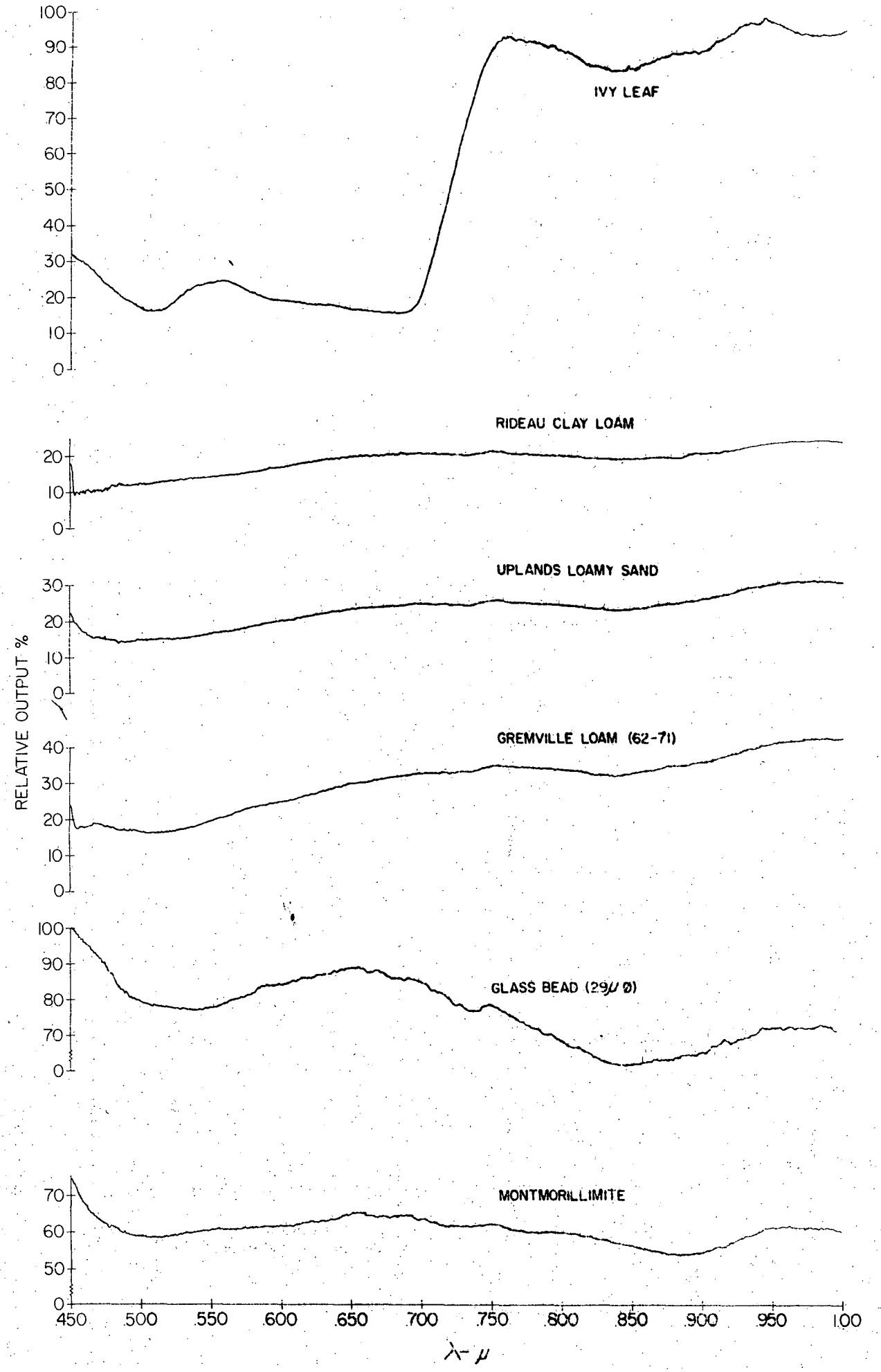

Figure 12a. Spectral curves of various soils in the spectral range of 0.450 μ to 100 μ.

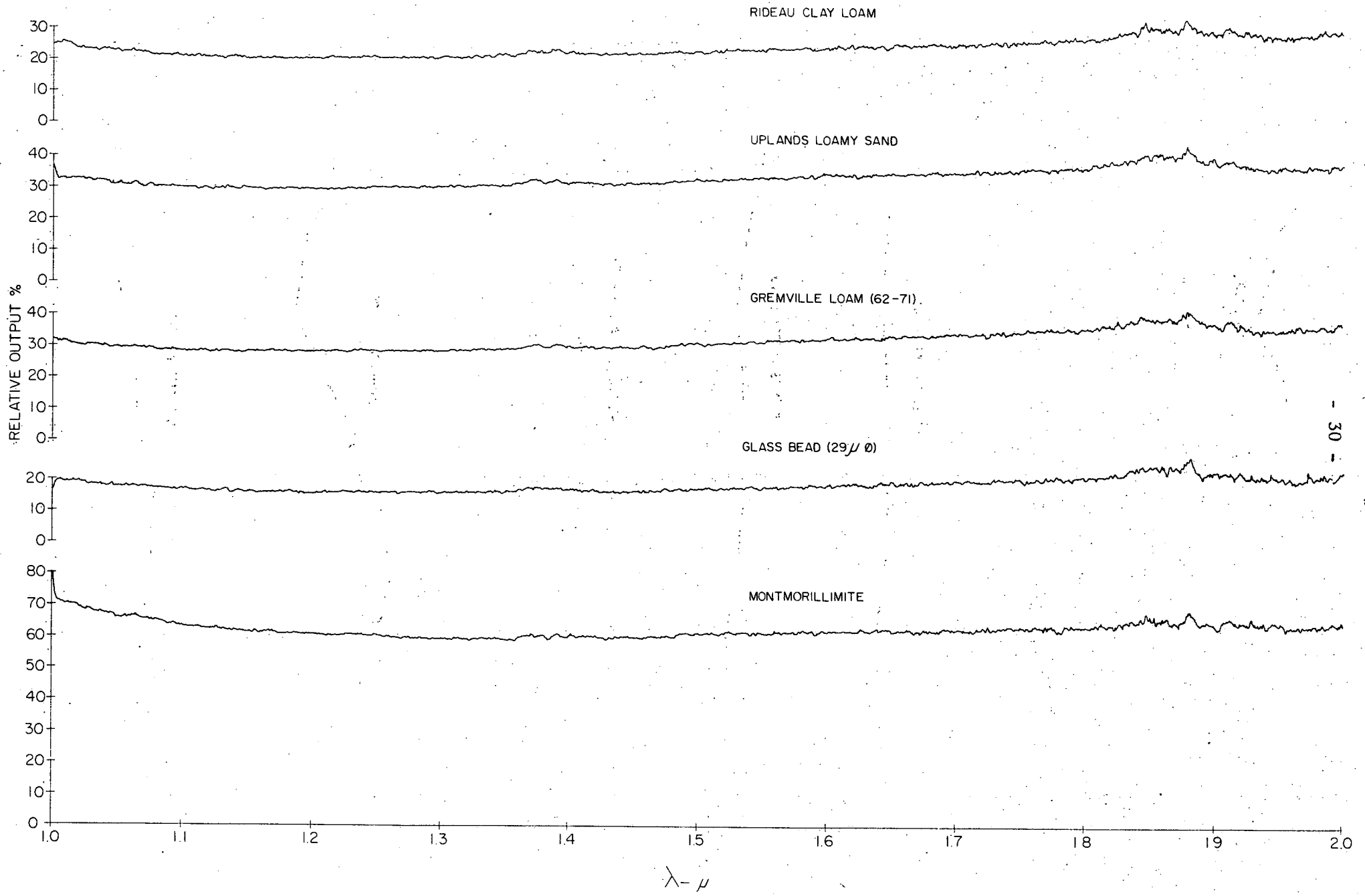

Figure 12b. Spectral curves of various soils in the spectral range of 1 μ to 2 μ.

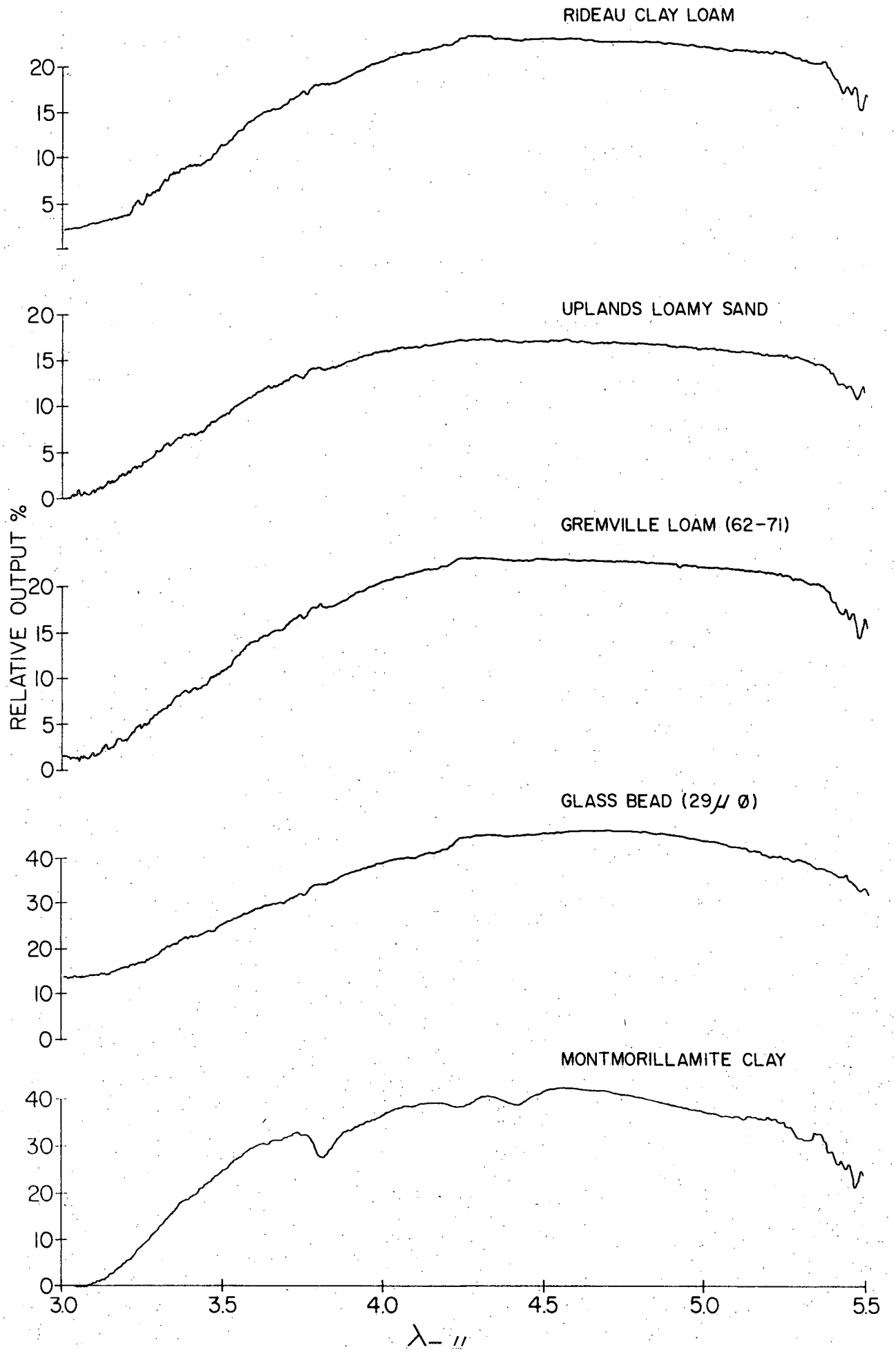

Figure 12c. Spectral curves of various soils in the spectral range of 3 μ to 5.5 μ.